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AIRBORNE SPECTRAL-RECONNAISSANCE SYSTEM
VELA CLOUD GAP PROGRAM

by
John E. Wilson, Project Manager
and
Callie Lukermann Craig
Charles W. Hanson
Donald H. Kelly
Thomas W. Mark
Donald S. Ross

prepared for
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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Vidya Project No. 9035

VIDYA

RESEARCH AND DEVELOPMENT

1450 PAGE MILL ROAD, PALO ALTO, CALIFORNIA

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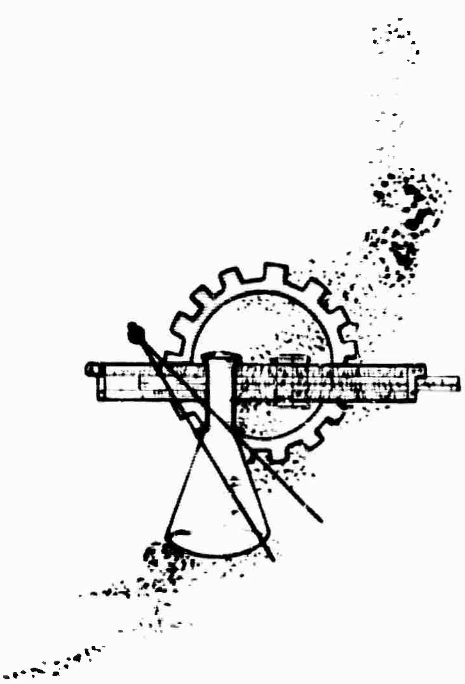
The word Vidya, taken from the Vedanta philosophy of the Hindus, means knowledge. The symbol used to denote the Vidya organization is the letter "V" from Sanskrit, the ancient language of India.



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March 20, 1965

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1450 PAGE MILL ROAD • PALO ALTO, CALIFORNIA
TEL: DAVENPORT 1-2455 TWX: 415 492-9270

FOREWORD

This is the final report prepared under Vidya Project No. 9035 on the airborne spectral-reconnaissance system for detection of underground nuclear explosions. This work has been performed under Contract No. AF 33(657)-7381 by the Vidya Division of Itek Corporation for Task 7.10 of the VELA Uniform (now VELA Cloud Gap) Program. The Advanced Research Projects Agency sponsors the VELA programs, and the Terrestrial Sciences Laboratory of the Air Force Cambridge Research Laboratory exercises technical cognizance.

Together with the five semi-annual technical reports, which it incorporates by reference, this report presents a comprehensive discussion of all work performed under Vidya Project No. 9035. It describes: work performed in the period June-October 1964 under an extension of contract for modification of the nine-lens camera and associated equipment; the final results of efforts to develop an airborne spectrometer system; and the computer program for the reduction of spectrometer data. It contains also a brief discussion of multiband photo analysis, drawn mainly from the work performed on the SHOAL event. Follow-on airborne spectral reconnaissance is being done under another contract and reported separately.

ABSTRACT

The nine-lens camera built as a prototype instrument for Project VELA has been redesigned and rebuilt, and is operating well. Redesigned or replaced parts in the new camera include: a stainless-steel shutter curtain; lenses individually focused for best resolution in each band; adjustable fiducial markers which allow optical registration in composite printing; new optical projection counters; a new electrical remote-control box and system console. Other improvements have been made to increase realiability and reduce maintenance. The Maurer P-220 cameras of the prototype multiband system have been replaced with Mitchell-Vinten F-95 70-mm reconnaissance cameras, which are performing more reliably.

The 14L Block spectrometer has been intensively tested, and previous difficulties with this instrument have been isolated. Its unsuitability appears to be due to the nonlinear response of the light-biased cadmium selenide detector. Nonlinearities cannot be corrected by means of the present data-reduction system. The 14L spectrometer, therefore, is not recommended for further use. The spectrometers with silicon solar detectors were satisfactory.

The preliminary system of analyzing spectrograms by visual inspection was replaced by a series of two computer programs: one to convert spectral data from paper tape to IBM cards, and a second to calibrate and correct the data at selected points over the spectrum.

A review and appraisal of multiband spectral analysis of the SHOAL event has been submitted separately, at the request of the project monitor. This document stresses the effects of human activity at unconcealed events and the necessity of timing reconnaissance to capture delayed as well as immediate indicators.

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AIRBORNE SPECTRAL-RECONNAISSANCE SYSTEM FOR VELA UNIFORM PROGRAM

1. INTRODUCTION AND PROGRAM SUMMARY

Under Task 7.10 of the VELA Uniform program sponsored by the Advanced Research Projects Agency, the Vidya Division of Itek Corporation was charged with the development and testing of an airborne spectral-reconnaissance system. The objectives of the system were: (a) to provide a means of detecting, recording, and displaying the physical and cultural manifestations of clandestine underground nuclear explosions; (b) to reduce the area of search for a suspected explosion; and (c) to determine the epicenter of the explosion.

The experimental research program undertaken by Vidya had as its principal purpose the investigation of direct or indirect effects of physical shock associated with underground nuclear explosions. Cognizance was taken of the fact that thermal, radiological, and chemical phenomena might complicate shock-induced effects. However, no attempt was made to investigate such phenomena under Task 7.10.

An additional purpose, added to the program in May 1964, was to determine whether it is possible to distinguish underground nuclear events from earthquakes of similar magnitude by means of airborne spectral reconnaissance. A special earthquake investigation was made with the cooperation of Stanford Research Institute and the U. S. Geological Survey.

The airborne spectral-reconnaissance program was based on the following technical assumptions:

(a) The airborne system will be used over a search area of about 500 sq. km.

(b) The search area will be defined and located by means other than spectral reconnaissance, mainly seismic sensing.

(c) The subsurface event will produce physical manifestations.

(d) Physical manifestations can be expected to affect vegetation, soils, rocks, and geologic structures.

(e) Spectral signatures can be established for significant objects and materials from available photographic and nonphotographic sensors.

(f) The subsurface event will produce changes in these signatures.

(g) The changes can be detected and amplified by techniques developed in the Vidya Division.

The fifth semi-annual report submitted in August 1964, described and evaluated the airborne spectral-reconnaissance system and the data analysis system. It also contained a definitive discussion of the work done under Contract AF 33(657)-7381 on four underground events: the nuclear detonations SHOAL and CLEARWATER, and the earthquakes near Nephi, Utah and Prunedale-Chittenden Pass, California.

This report describes the modification of the nine-lens camera and associated equipment, authorized by AFCRL on May 6, 1964 under an extension of contract, and the work done since August on spectrometer data reduction and analysis. It also contains a brief discussion and evaluation of multiband photo analysis as a means of detecting clandestine underground nuclear explosions. Follow-on airborne spectral reconnaissance, which will serve to confirm and extend this evaluation, has been authorized under a separate contract and will be fully reported elsewhere.

2. MODIFICATION OF NINE-LENS MULTIBAND CAMERA

The nine-lens camera built for Project VELA under Contract No. AF 33(657)-7381 was designed and constructed as a prototype instrument. The very heavy flight schedule of 1963 exhausted the life of many components of the VELA camera, to the extent that a major reconstruction would have been necessary to restore it to use. Experience had suggested many changes in design which promised to improve performance and reliability of the camera, so a reconstruction of the original prototype was not considered advisable. Vidya therefore requested and obtained approval from AFCRL to undertake a major redesign of the VELA camera. This work has, in effect, produced a completely new instrument.

The new VELA camera has been used on test and operational flights. Its improved performance and the high quality of the photography demonstrate the success of the redesign.

The following major changes have been made to the original VELA multiband camera.

2.1 Camera Body

A new camera body was required for the modified camera because access and cable-connector holes had been relocated, and room had to be provided for internal clearances to operate the new shutter. The new body (Fig. 1) retains the same general dimensions as the prototype.

2.2 Shutter

Vidya has designed a new shutter assembly (Fig. 2), which incorporates in one rigid structure the nine format apertures, the shutter, rollers, drive mechanism, film windover motor, and gearing. The whole shutter assembly lifts out of the camera body, and is disconnected electrically through its own set of connectors. It can be run and bench-tested as a separate unit.

The triple shutter curtain of the prototype camera was replaced by a single stainless-steel shutter curtain. The new curtain has nine exposure slits, each 0.204 inch wide, stiffened on either side by aluminum strips which define the slit opening precisely. A capping curtain of similar construction was also made. The curtains are finished in matte black epoxy paint.

The redesigned shutter uses a two-speed motor and double clutch to permit four speeds, nominally 1/30, 1/60, 1/120, and 1/240 seconds. The 1/240-sec speed has been operated successfully under test, but the design appears to be approaching its safety limits, owing to the high curtain velocity and the large inertia of starting and stopping. The 1/240-sec speed has been inactivated pending final design review. The other three speeds are fully operational, giving much more flexible response to flying conditions than was possible with the single shutter speed of the prototype camera.

2.3 Lenses

Vidya wished to substitute 6-inch Leitz C-106 f/2.4 high-resolution lenses for the 6-inch Schneider Xenotar f/2.8 lenses used in the prototype camera. Funding to make this change in the VELA camera was not available, and the Schneider Xenotar lenses were reinstalled in the new camera body.

In the prototype VELA camera, each lens was focused to give approximately the same scale, rather than best resolution, to permit registration of composite images with the minimum of trouble. Average resolution was 10 to 20 lines per millimeter.

Each lens of the modified camera has been focused for best resolution, and the retaining glasses, which held the filters in front of the lenses, have been removed. The gelatin filters are now held by snap-rings on the diaphragm assembly between the lens elements. Flight tests with the refocused lenses showed that resolution had been increased to 25 to 30 lines per millimeter with high-contrast targets on Plus X Aerographic film. With accurate image-motion compensation (see Section 2.8), resolution may improve still more.

The back focal distance of each lens was measured by the National Bureau of Standards, with filters in position, on the correct film emulsions.[1] Lens-mounting spacer rings were ground according to the NBS dimensions. For some unknown reason, possibly a shift of the infinity focus of the NBS collimators when viewed by the lenses with filters in position, the dimensions as given turned out to be inexact, and the lenses had to be refocused by as much as -0.019 inch to 0.039 inch to obtain best resolution. This refocusing entailed a great deal of additional work. Figure 3, a photograph of the camera interior, shows the refocused and reinstalled Schneider lenses.

The Schneider lens has a larger field than is utilized on the 70-mm format. Stray light, reflected from the internal baffle-plates which partitioned each lens from its neighbor, caused unncessary flare in the prototype camera. Flare has been substantially reduced in the modified camera by redesigning the partitions in the form of blind louvres.

2.4 Fiducial Markers

The fiducial marks on the prototype camera were fixed pinpoint holes drilled in the format plate. Fixed fiducials were satisfactory with the original matched lenses, but the change to individually-focused lenses in the modified camera allowed slight variations in image size. A new fiducial marking system, which permits each marker to be moved, was therefore designed. The fiducial marks on each format can now be set to standardize scale between individual exposures and achieve registration by optical means during composite printing. Figure 4 shows the new fiducial-marking system.

2.5 Optical Projection Counters

During the redesign of the shutter assembly, it was found necessary to modify the frame-numbering optical projection counter to fit under the new curtain rollers. Three off-axis projectors, one for each film path, project numbers from an electrically operated three-digit counter onto the

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[1] See Appendix A.

areas of bands 3, 6, and 9. Individual bands are identified by notches cut in the edges of the format masking plate.

2.6 Film Magazine

The A9B film magazine was reworked and rebuilt to fit the new camera body. Dowel pins were designed into the magazine to permit accurate location on the body and to pick up the film-wind drive dog with better alignment. The guides for the individual film tracks were redesigned.

Vidya originally proposed to obtain a spare film magazine for quick reloading of the camera in flight. This purchase was not authorized by AFCRL. However, the addition of film spool locating pins in the magazine makes for faster in-flight reloading tha was possible in 1963.

2.7 Camera Control Box and System Console

A new electrical remote-control box was designed and made for the modified camera. It controls all power to the camera, the cycle rate, shutter speed, and (in conjunction with an intervalometer) exposure interval timing. Fuses for the 28-volt dc and 115-volt ac power lines are also provided. Figure 5 shows the new control box.

Three plug-in circuit boards with solid-state elements permit rapid replacement of components for the timed circuits which control the 115-volt 400-cycle shutter motor.

Figure 6 shows the controle console for the complete multiband and color photographic system. The console is shock-mounted on a frame which bolts to attachment holes in the floor of the aircraft.

2.8 Hycon Image-Motion Compensation System

The IMC system used on the prototype A9B camera magazine has been a source of continual difficulty, tending to fail at low IMC rates when moderate vacuum is used to flatten the film during exposure. This particular system was never put into production, and only a few units were made. Several of the components were specially made, and spares are almost impossible to obtain. The A9B magazine can be controlled by other IMC systems, which are produced in quantity and are in service with the Air Force. To ensure future operational reliability, the use of another IMC system with the modified [illegible]LA camera should be considered.

2.9 General

The general camera design has been improved by replacing sleeve bearings with ball bearings, improving alignment of running parts, and by dowelling and pinning various components. Both the film drive and the shutter drive now have overload clutches, which will prevent major damage in the event of a jam. These improvements will increase reliability and reduce maintenance requirements.

3. SUBSTITUTION OF MITCHELL-VINTEN CAMERAS

With the authorization of AFCRL, Vidya purchased three new Mitchell-Vinten F-95 70-mm cameras to replace the Maurer P-220's,which had proved unreliable in the 1963 flight operations.

The new cameras were ordered with Leitz 6-inch f/2.8 lenses already fitted, to save the cost of converting the Schneider lenses from the Maurer cameras. They were fitted with slow-speed shutter curtains (1/300 and 1/600 sec) and were modified internally for single-pulse operation.

The camera mount was modified to accept the Mitchell-Vinten cameras, and a remote control box was designed for operation on single pulse and intervalometer control modes. Solid-state circuits were used in this design. Figure 7 shows the Mitchell-Vinten cameras and control boxes.

The new cameras and lenses have been operated successfully. The quality of the Ektachrome and camouflage-detection color photography is superior to that obtained previously with the Maurer cameras.

4. AIRBORNE SPECTROMETRY AND SPECTRAL DATA ANALYSIS

4.1 Background

Partly on the advice of ARPA project monitors, three Block Associates spectrometers were selected for the use in the airborne spectral reconnaissance system. These instruments use the Michelson interferometer principle to obtain high sensitivity, but they do not record a spectrogram directly. They are small an light, have a rapid scan capability, and can be used with various detectors to cover various spectral ranges. The spectrometers originally chosen were: a Model I4L with silicon solar cell, sensing from 0.5 to 1.0 micron; a Model I4S with lead sulfide detector, sensing from 1.0 to 3.0 microns; and a Model I4E with indium antimonide detector, sensing from 3.0 to 5.0 microns.

Preliminary vibration tests showed that the spectrometers would not operate properly at loads greater than 0.03. Since the oscillating mirror in each spectrometer was sensitive to vibration, the g-loading on the instruments was measured during a test flight. This indicated the need for an anti-vibration mount, as discussed below.

The airborne system as a whole was flight-tested in September 1962 and January 1963. No spectrometer data were obtained on the first test flight, owing to data-recording malfunctions. These were corrected, but the data obtained on the second flight were invalid because of excessive vibration. To remedy this defect, new isolation mounts, which suspended each spectrometer head on a thin rubber membrane, were fabricated and installed. Foam padding around the spectrometers dampened gross lateral and vertical movements. A rocking mirror provided image-motion compensation. Flight tests made during April 1963 showed that the new mounts were satisfactory.

The original system of three airborne spectrometers was intended to obtain continuous spectra up to about 5 microns. In 1963, a number of factors - exigencies of flight operation as well as intrinsic characteristics of the spectrometers - forced us to lower the sensing limit from the original 5.0 to 3.5 microns. In the meantime, NRDL began work on an experimental infrared-sensing program, so the reduction of the spectrometer sensing range was not considered a serious loss.

Vidya had designed the spectrometer system on the assumption that the camera window of the RC-130, a borosilica glass plate half and inch thick, would be removed during operation of the spectrometers. At the time of installing the instruments in the aircraft, we were informed that this could not be done. Early flight tests showed that the indium antimonide detector of the I4E spectrometer was failing to sense beyond 2.4 microns through the camera window. The radiosonde opening of the aircraft was therefore modified to receive a new isolation mount for the I4E. The new mount was identical with the other two except for a cover plate intended to seal off the opening and maintain cabin pressurization when the spectrometer was not in use. Image-motion compensation at the new location was provided by a servo link from the mirror at the camera window. This proposed arrangement was not put into operation, since environmental testing of the I4E detector showed that it was not sensitive enough at ambient temperatures to register earth radiation in the 3.0 - 5.0 micron range.

Block Associates, when informed of our difficulties with the I4E spectrometer, recommended replacing the indium antimonide detector with a lead selenide detector sensing from 2.0 to 4.5 microns. This modification, made by Block in June 1963, proved disappointing when tested in the airborne system, and was never used in operational reconnaissance flights.

Instead, the airborne system was reduced to two units: the I4L with a light-biased cadmium selenide detector, sensing from 0.35 to 1.0 micron, replacing the original silicon cell; and the I4E with a lead sulfide detector, sensing from 1.0 to 3.0 microns, replacing the unsatisfactory lead selenide. These detectors shifted the spectrometer sensing range downward, eliminating some of the middle infrared but including the photographic blue-violet (roughly corresponding to band 1 of the multiband camera system). The I4S spectrometer, now eliminated from the airborne system, was later equipped with a dual detector unit (cadmium selenide and lead sulfide) which duplicated the sensing range of the airborne pair. It was then put into use for ground spectrometry.[2]

In the operational flights conducted in fall and winter of 1963, the performance of the two airborne spectrometers appeared to be compromised by uncontrolled angular motion within the rubber-basket isolation mounts. In February 1964, a flight test experiment was made to determine the amount and effects of uncontrolled angular motion. The experiment (described in the fifth semi-annual report) led to the conclusion that the major errors were caused by mount placement or IMC drive or both, rather than basket wobble. These errors could have been corrected by redesigning the basket mount to improve the alignment of the optical axis of the spectrometers. In the meantime, however, the nonlinear behavior of the light-biased cadmium selenide detector (see next section) had convinced us that further engineering effort on this instrument was not justified.

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[2]Ground spectrometery for Project VELA is described in the fourth and fifth semi-annual reports.

4.2 Spectrometer Performance Tests

Early in 1964, the I4L instrument (which had been equipped with a light-biased cadmium selenide detector in the fall of 1963) was subjected to a simple optical test with a sample of dydimium glass. This is a multi-banded filter whose transmittance is accurately known as a function of wavelength, both from the manufacturer's catalogue and from our own measurements on the Cary Model I4R Spectrophotometer. The spectrometer was pointed at an illuminated white card with and without the dydimium filter, and the two spectra were plotted in the usual way (with the wave analyzer and x-y plotter), so that the ratio of these two responses should equal the transmittance of the dydimium glass. In effect this test uses the Block instrument as a spectrophotometer.

If the instrument is working properly, this procedure has the virtue of testing a number of things at once: wavelength scale, amplitude response, spectral sensitivity, signal-to-noise ratio, linearity, and spectral resolution. Unfortunately, the results of this test were quite poor, and more specific diagnostic tests were made during March and April to find out why.

As shown in Figure 8, the spectral resolution of the I4L was only slightly below the theoretical limit imposed by the mirror scan length, but there was a large nonlinearity in the intensity scale. In the figure there also seems to be a large nonlinearity in the frequency scale. We later learned that most of the apparent wavelength error in the spectrogram was caused by amplitude nonlinearities in the interferogram, but we could not at first rule out the possibility of other defects in the system.

Nonlinearities in the interferogram may be caused by improper motion of the scanning mirror, nonlinearity of the photodetector, or both. In order to separate these two potential troubles, we generated a synthetic interferogram in the form of periodically triggered flashes from a General Radio Strobotac. With the mirror scan disabled, the response to this interferogram is controlled only by the detector and pre-amplifier characteristics. Since these flashes are essentially delta-functions, their spectrum should be flat over the frequency range of the instrument. Furthermore, if the system is linear, the shape of this output spectrum must be independent of the intensity level of the input flash-train.

In order to test the mirror motion as well as the detector characteristic, we used a single spectrum line as the input (the 5461 Å line of mercury) so that the interferogram would be essentially sinusoidal. In this case, the spectrum should be a single spike whose bandwidth depends only on the scan length of the interferometer and the bandwidth of the harmonic analyzer. This test was repeated with the instrument pointing up, down, and sideways, to determine whether the frequency conversion factor remained constant, as it should unless there are significant changes in the mirror velocity. Essentially the I4L passed this test satisfactorily. Wavelength errors were only a few percent, attributable mostly to backlash in the frequency drive of the harmonic analyzer.

However, the results of the above-mentioned amplitude linearity tests with the Strobotac showed where the trouble was. By inserting neutral density filters in front of the instrument, the output spectra of the flash interferograms were measured at various intensities over a range of 1000:1, and the resulting spectrograms were plotted on a log intensity scale. These curves should all be parallel to each other. Actually, as shown in Figure 9, they cross at the highest intensities, and diverge significantly below about 1,000 cps even at lower intensity levels. This behavior is almost certainly due to the nonlinear response of the biased cadmium selenide detector.

From these results, we predicted that it should be possible to obtain a better dydimium glass curve by using the highest scanning velocity of the mirror, and very carefully selecting the right intensity level. This prediction was experimentally confirmed.

With this type of nonlinearity in the photodetector, the I4L cannot obtain reliable spectral data. There is no way to correct for nonlinearities in the interferogram by means of the present data-reduction system, since the computer does not receive the interfereogram but only a wave analysis of it. If the detector nonlinearity were independent of frequency, it could conceivably be corrected by feeding the recorded interferograms directly into a suitable computer program and abandoning the present data-reduction system; but this is not the case. Since these tests were made, the modified I4L has not been used, and data reduction has been confined to data obtained with other detectors.

4.3 Preliminary Data-Reduction System

The preliminary system for reduction of spectral data is shown in Figure 10. It consists essentially of:

(a) A frame selector for selecting the interferogram corresponding to the frame of multiband photography to be analyzed.

(b) A four-channel tape playback system, one channel for each of the three spectrometers and a fourth to analyze accelerometer information in the airborne operation. The primary information was played back onto the buffer loop and then into the actual reduction equipment. Later the accelerometer channel and one of the spectrometer channels were dropped.

(c) A wave analyzer and x-y recorder. The data in the form of interferograms were fed into the wave analyzer. The output of the wave analyzer was then coupled to the x-y recorder,which gave a spectrogram, or graph of relative response versus wave number.

The spectrograms produced by this preliminary system were analyzed by visual inspection. This proved unsatisfactory for several reasons:

(a) The method was too slow to analyze large masses of data, especially when ground spectral analysis was added to the airborne operation.

(b) Because of the cumbersome form of the data, analysis could not be based on a statistical or mathematical approach.

(c) The spectrograms were not easily correlated with the multiband photography because they included all frequency and wavelength dependencies of the system, such as the spectral response of the photodetectors and the frequency response of the tape decks and amplifiers. These factors could not be readily sorted out while the data were in the form of raw spectrograms.

4.4 Modification of Sy tem

The above problems led to the submittal, in July 1963, of Vidya Proposal No. 3629, "A Proposed Equipment Design and Computer Program for the Reduction of Spectral Data," to change the preliminary system of data reduction to a two-part system. Part A of the proposed system was data translation equipment for transforming the interferograms stored on magnetic tape into frequency spectra, and then converting these spectral data from analog form to a digital form suitable for input to a digital-computer system. Part B was a computer program for analyzing and reducing the data to a form suitable for comparison with the other phases of the VELA operation. The proposal was accepted in December 1963 as a change in scope of Contract AF 33(657)-7381.

4.4.1 Data-translation equipment

The spect' ter data were converted from analog to digital form by means of the sy... shown in Figure 11. The input to the equipment was a series of interferograms, each containing the Fourier transform of the desired spectral information. The equipment was required to analyze one frequency at a time, average the amplitude for a series of interferograms at a given frequency, convert this average to digital form, and punch the result onto paper tape. The equipment than automatically incremented to the next frequency and repeated the cycle until the frequency spectrum of interest had been scanned.

In addition to processing the basic interferogram, the equipment was required to monitor the average total interferogram amplitude as a key to recorded intensity level, and to print coded information which identified the gain settings and basic calibration data for use in the computer program. It was therefore required to measure the transfer functions and the possible sources of error of the various spectrometers and their associated equipment, so that the information fed into the computer could be converted as accurately as possible into the actual spectral distribution of light received. In this way, the data-translation equipment generated a set of data points with sufficient known information about them to do a statistical analysis or spectral comparison in the computer.

The airborne spectral data were recorded with no reference standard; hence, the output data are directly proportional to the system transfer function, which must be completely known. In the ground survey, a known reflectance was used beside the sample to standardize the measurements under actual operating conditions.

The translation equipment was controlled by a digital-control logic system which provided timing, sequencing, and operating functions. As the equipment was constructed, difficulties in timing and sequencing arose and the control logic had to be modified, causing some delay in the date of completion. When calibration of the data-recording equipment was attempted, during the construction and debugging period, several other problems were encountered.

(a) The condition of the data-gathering equipment at the time of recording data was unknown.

(b) The airborne and ground data required different operations for final computation, because of the lack of calibration standards in the air.

(c) Tests of the spectrometer (see Section 4.2) had shown nonlinearities that could not be accounted for by calibrating the airborne instrumentation. At this time, the airborne data were set aside and attention was focused on getting the equipment into operation for the reduction of the ground spectral data.

The decision had been made at this point to discard the search for spectral line pair ratios, and instead to present the final data as curves of reflectance versus wavelength. This decision required a minor modification of the equipment and a new approach to the computer program (see next section).

With the equipment modified and the new computer program written, a preliminary checkout of the system was made. Final checkout and operational reduction of VELA data could not be done at this time because of lack of funding.

During the summer of 1963, the ground spectrometer system had been used on a noninterference basis to collect spectral data on grapes in the field, as a means of determining the optimum film-filter combination for an agricultural aerial survey. The data collected were in the same form as those from SHOAL and CLEARWATER, and were reduced in the same manner as the VELA data would have been. While the reduction was being done, minor modifications were made to the data-translation equipment and the computer program to accommodate the data in the best possible manner.

Some of the data thus reduced are included here to illustrate the best results obtainable with the silicon solar-cell detector. Unfortunately, all the operational VELA data were taken with the light-biased cadmium selenide detector, and were therefore unusable, as explained in Section 4.2.

In the course of this work, the problems of collecting and reducing these data were better defined. Among the most serious problems were:

(a) The variations in gain and/or illumination level between sample and standard at the time data were collected.

(b) The large range of light intensity levels. Light intensity varied beyond the linear range of the instrument, and also required the reduction program to perform over these ranges.

(c) The high noise level (or low signal-to-noise ratio).

Under these conditions, the data were reduced, a statistical analysis was made to diminish the errors, and a set of curves was generated. Figures 12 and 13 are examples of these curves, which show the most probable spectral reflectance of a subject as a function of wavelength, along with the one-sigma limits.

Figure 14 shows the spectral reflectance of a variety of soils. There is a notable spread in reflectance between different types of soil, especially between the dark and the light sandy soils, which differ by a factor of about ten.

This program of data reduction has pointed out several problems in the use of an interferogram system as a means of collecting field spectral data. A thorough evaluation of these problems would be required before any concrete recommendation as to future use of the data-gathering and reduction system could be made.

4.4.2 Computer program

The original requirements for a computer program to reduce and analyze spectrometer data were modified as the difficulties of calibration and data reduction came to light. Early in the study, when the true complexity of the necessary analysis and the condition of the basic data began to be appreciated, the plan for analysis suggested in the proposal - correlation of spectral line pair ratios by automatic computer - was discarded. Emphasis was shifted to the development of a computer program to accept the output of the data-reduction equipment and apply the appropriate calibration and correction factors to the spectrometer data at selected points over the spectrum. The analysis was to be performed later by visual comparison because of the human judgment required for evaluation. However, contract funding was insufficient to cover this aspect of the study.

Two computer programs were developed in this project. The first, subcontracted by Control Data Corporation for execution on a CDC 160, was a short program for converting the data from paper tape to cards. This was required to bridge the gap between the paper tape output of the data-reduction equipment and the card input of the IBM 1620 computer leased by Vidya. The 1620 was then used for the correction and further reduction of the spectrometer data. This second computer program is discussed here.

4.4.2.1 Input

The input to the computer program consists of two sets of data: calibration data and spectrometer data. The calibration data consist of the following tabulations.

(a) Calibrated values of the radiance (or reflectance) of the standard for the first spectrometer as a function of wavelength.

(b) Calibrated values of the radiance (or reflectance) of the standard for the second spectrometer as a function of wavelength.

(c) Frequency response (gain versus frequency) of the spectrometer and recording system for a tape speed of 1-7/8 ips.

(d) Frequency response (gain versus frequency) of the spectrometer and recording system for a tape speed of 3-3/4 ips.

The spectrometer data consist of two parts, initial data and spectral-response data. The initial data are made of the following five entries, each containing no more than four digits.

(a) An identification code or sample or standard number.

(b) An indicator showing whether the spectral data to follow were taken for a sample or were from the standard.

(c) An indicator of the tape speed for recording the spectral data to follow, either 1-7/8 or 3-3/4 ips.

(d) The potentiometer setting which controlled the recording level during the time the spectral data were obtained.

(e) The product of frequency and wavelength (f/λ) for the spectrometer used in recording the spectral data. This value was keyed to the calibration data to be applied to the spectral data.

4.4.2.2 Output

The computer program outputs the calibration data, for documentation and identification of the computer run, and the corrected radiance (or reflectance) for each sample. These corrected radiances (or reflectances) are computed and output for each value of wavelength for which calibration data have been specified.

4.4.2.3 Method of calculation

The method of calculation is essentially simple proportion. At a given wavelength, the ratio of spectrometer response to actual radiance (or reflectance) is a constant. Thus, the ratio of the actual radiance (or reflectance) of a sample R_{sam} to the spectrometer response for the sample S_{sam} is the same as the ratio of the actual radiance (or reflectance) of the standard R_{std} to the spectrometer response for the standard S_{std}:

$$\frac{R_{sam}}{S_{sam}} = \frac{R_{std}}{S_{std}}$$

and

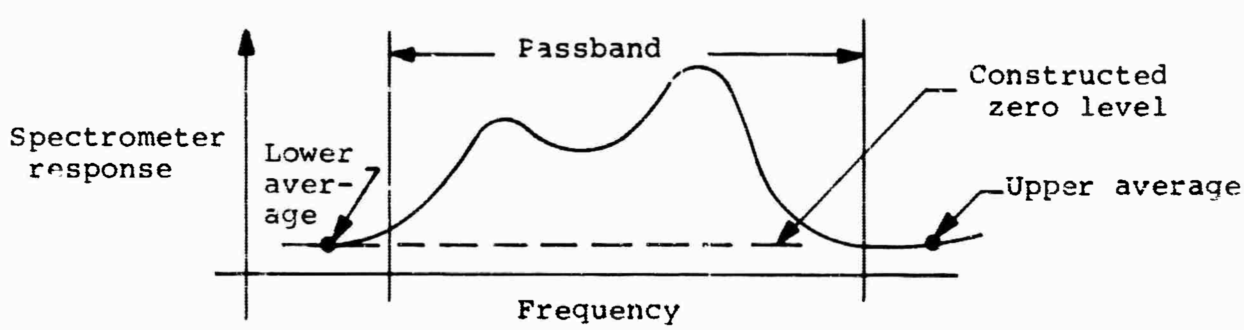
$$R_{sam} = S_{sam} \left(\frac{R_{std}}{S_{std}} \right)$$

The actual radiance (or reflectance) of the standard is given by the calibration data. The spectrometer responses for both the standard and the sample are provided by correcting the output from the data-reduction equipment for the following factors: potentiometer setting, wave-analyzer attenuator setting, and frequency respo[illegible] of the recording system.

Since the spectrometer responses [illegible]th the sample and standard are given at arbitrary frequencies, which do not necessarily correspond to the wavelengths specified in the calibration data, an interpolation scheme is required to evaluate the actual radiance (or reflectance) of the sample at the wavelengths specified for the standard. For this program, second-order interpolation, using the three data points nearest to the wavelength of interest, is employed.

For corrections of the spectrometer response using the frequency-response calibration data, interpolation is also required. In this case, linear interpolation of the frequency-response table is used.

A final correction of the spectrometer data, which was incorporated when the computer program was nearly completed, has to do with the apparent shift of the zero of the response curve due to background noise in the system. In order to correct for this effect, the spectrometer data are scanned above and below the frequency range of significant spectrometer response. Data in these regions are averaged and a straight line is constructed between the lower average and the upper average. This straight line is used as the correction to the zero level, as indicated in the following sketch.



4.4.2.4 Program improvements

Two suggestions are offered here for making the program more useful in the correction of spectrometer data. Had funding permitted, these modifications would have been incorporated during the present study.

(a) The program should include the scanning of data in the regions above and below the range of significant spectrometer response to detect the zero shift. As the program stands now, it computes the lower average and uses a pre-assigned value of slope to construct the zero response line.

(b) The interpolation of spectrometer response should be made more sophisticated. The present method of using second-order interpolation on the given data points nearest the point of interest should be replaced by a scheme which makes greater use of the available data and smooths the numerical results. A least-squares fit of a low-order curve to a larger number of points should be considered first.

A listing of the computer program is included as Appendix B of this report.

5. MULTIBAND SPECTRAL RECONNAISSANCE

The fifth semi-annual report, here incorporated by reference, described in detail the reconnaissance and data analysis performed by Vidya under Contract AF 33(657)-7381 on four underground events, including the two nuclear detonations SHOAL and CLEARWATER. Under a separate contract,[1] Vidya has made a follow-on ground survey of the SHOAL site, has performed follow-on airborne reconnaissance at both SHOAL and CLEARWATER, and has participated in pre- and post-shot reconnaissance for the SALMON detonation in October 1964.

The information derived from this additional work has, in general, confirmed the conclusions stated in the fifth semi-annual report. In Vidya Report No. 164, dated December 4, 1964, we submitted an appraisal of multiband spectral analysis as a means of detecting underground nuclear explosions, with particular reference to immediate and long-term effects observed at SHOAL. Two major considerations discussed in this report are:

(1) Human activity before and after an unconcealed event mutilates the natural landscape so severely as to confuse and even obliterate the directly shock-induced effects which we were seeking in our 1963 reconnaissance operations.

(2) Proper timing of reconnaissance flights, informed by thorough knowledge of the particular environment, is necessary for identification of an operationally suspect site. In the growing season following the SHOAL and CLEARWATER shots, significant changes in plant ecology occurred. Analogous changes can be expected, perhaps predicted, in other environments,

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[1] Contract AF 19(628)-4766, dated October 13, 1964.

and are likely to prove more reliable indicators than immediate shock-induced effects such as fracturing. In our opinion, therefore, comparative analysis of pre-shot (if available), immediate post-shot, and delayed post-shot multiband photography is an essential element of an operational airborne photographic-inspection system.

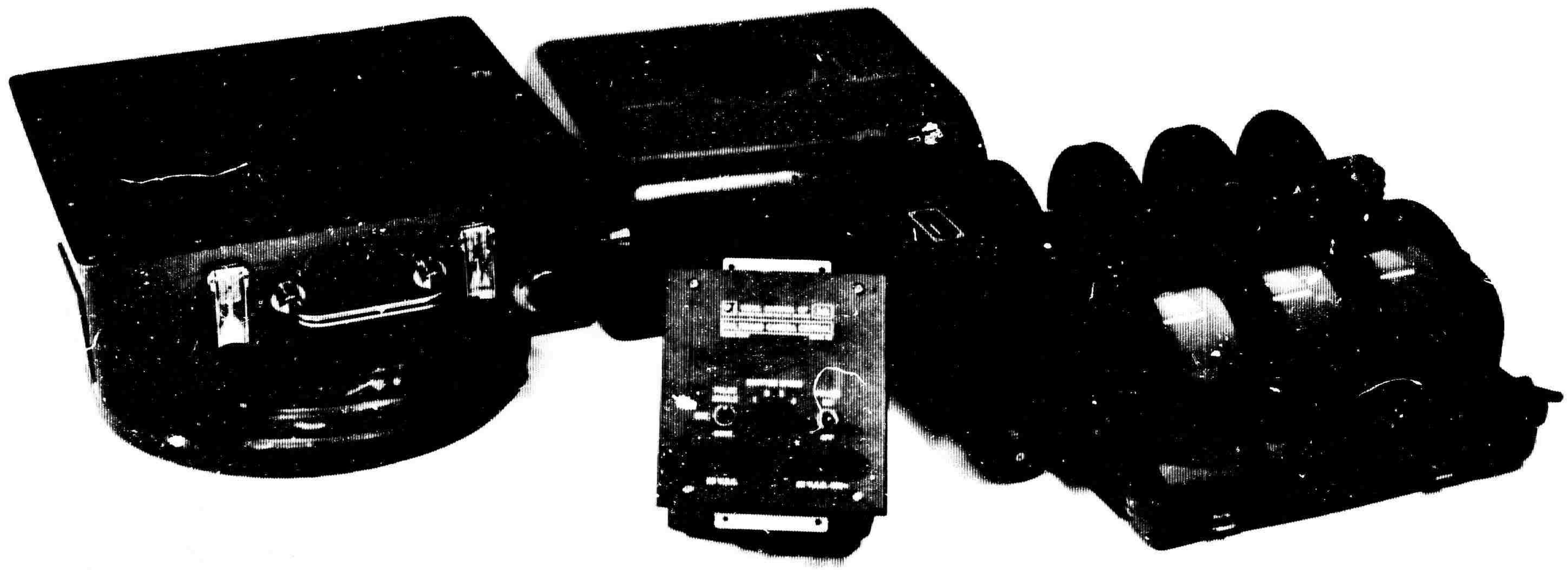

Figure 1.- Modified multiband camera showing the nine focal planes and adjustable fiducial markers, magazine cover, control unit, IMC drive, and open magazine with film spools.

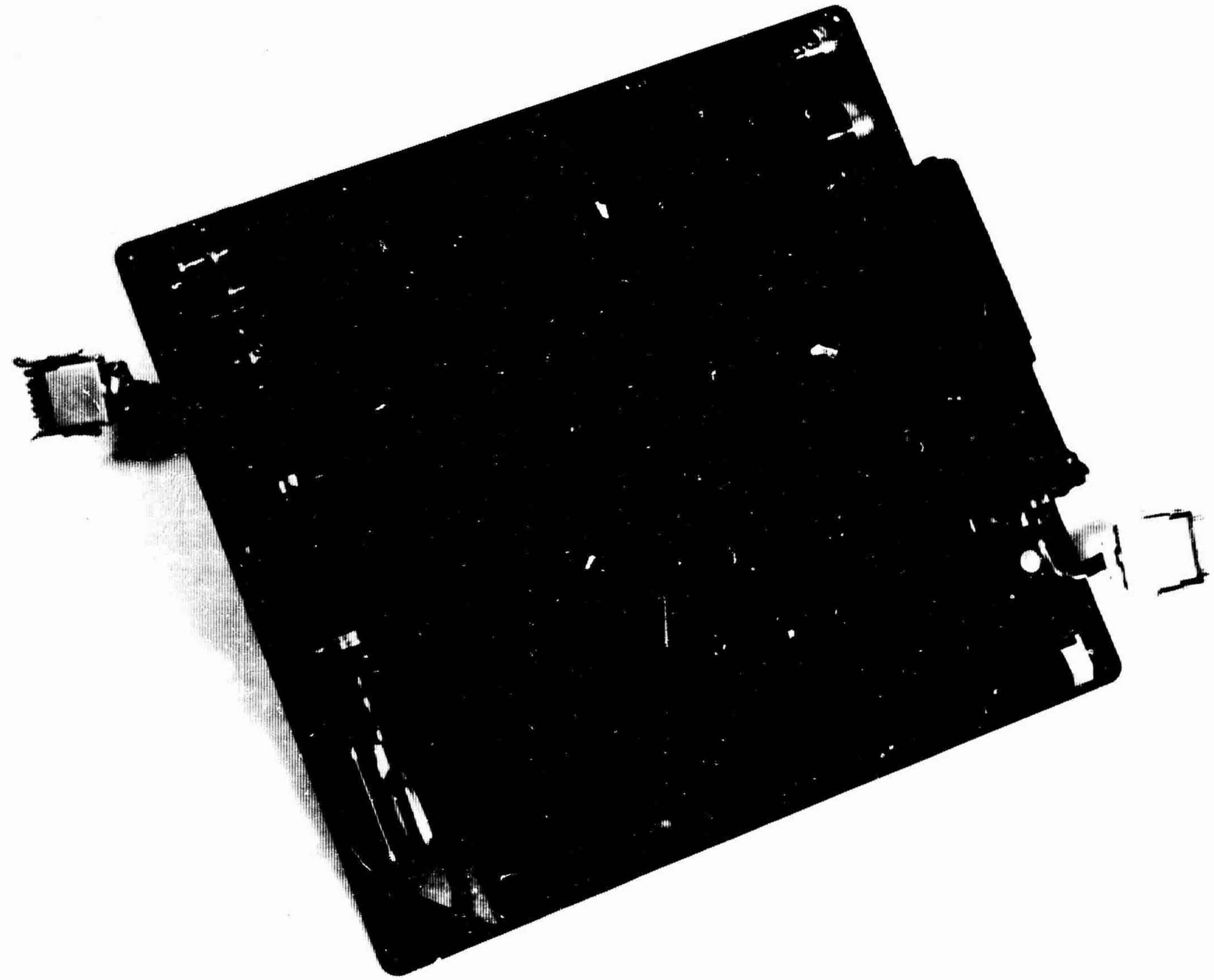

Figure 2.- Shutter assembly of modified multiband camera. Stainless-steel shutter curtain has nine exposure slits.

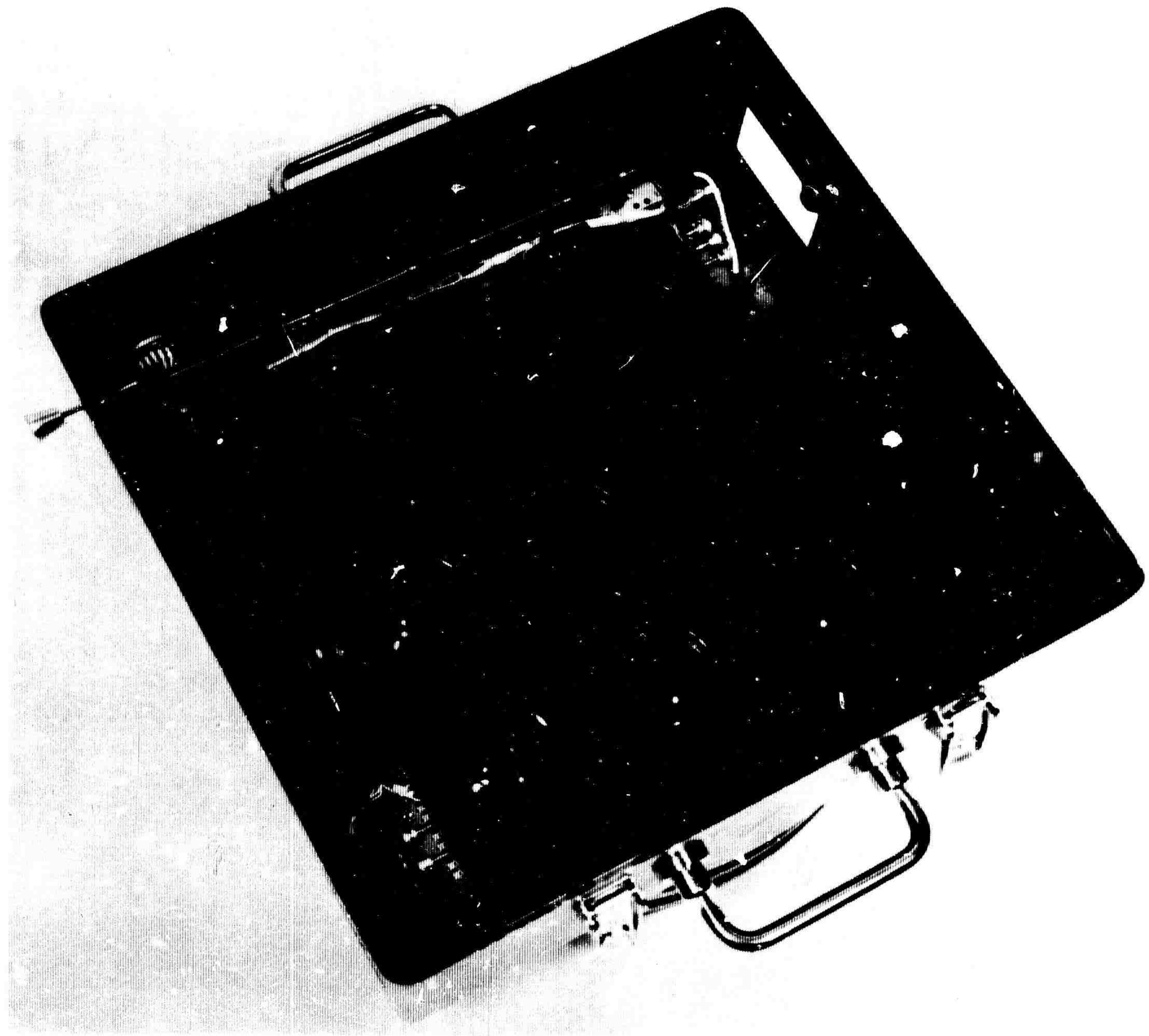

Figure 3.- Camera interior showing refocused Schneider lenses in place.

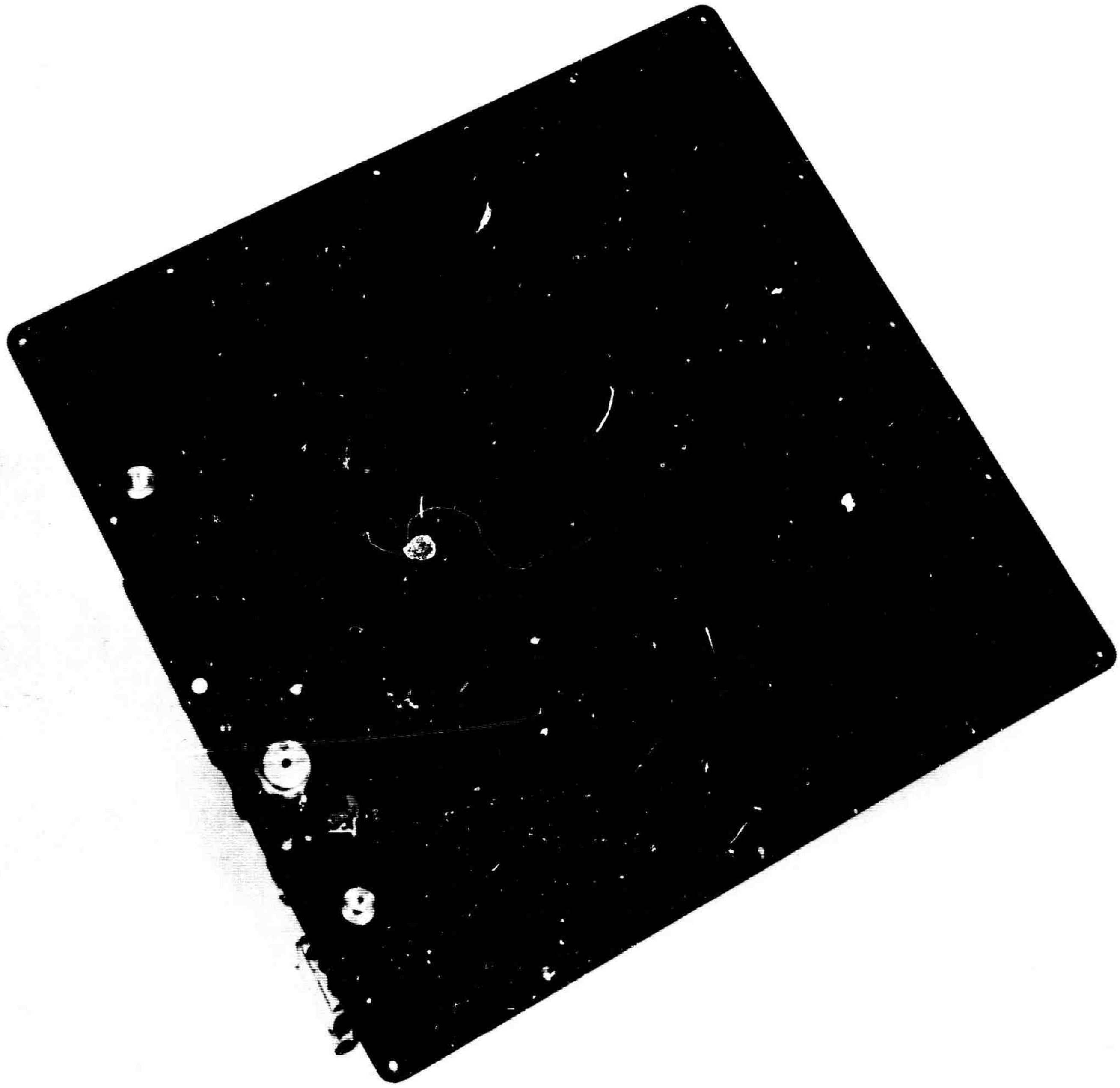

Figure 4.- Movable fiducial markers can be set to compensate for scale difference between frames of each exposure.

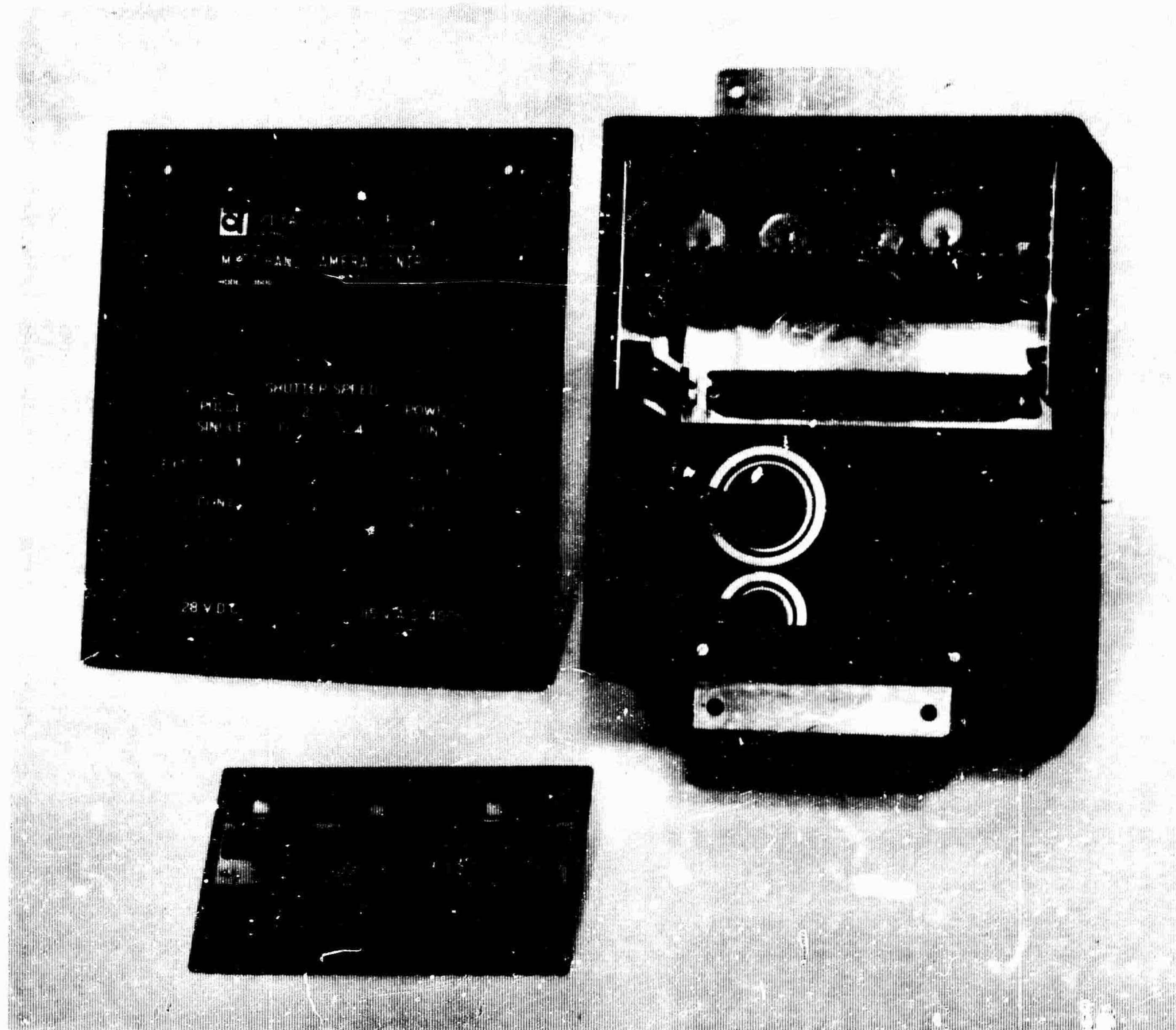

Figure 5.- Detail photo of new control box for modified multiband camera.

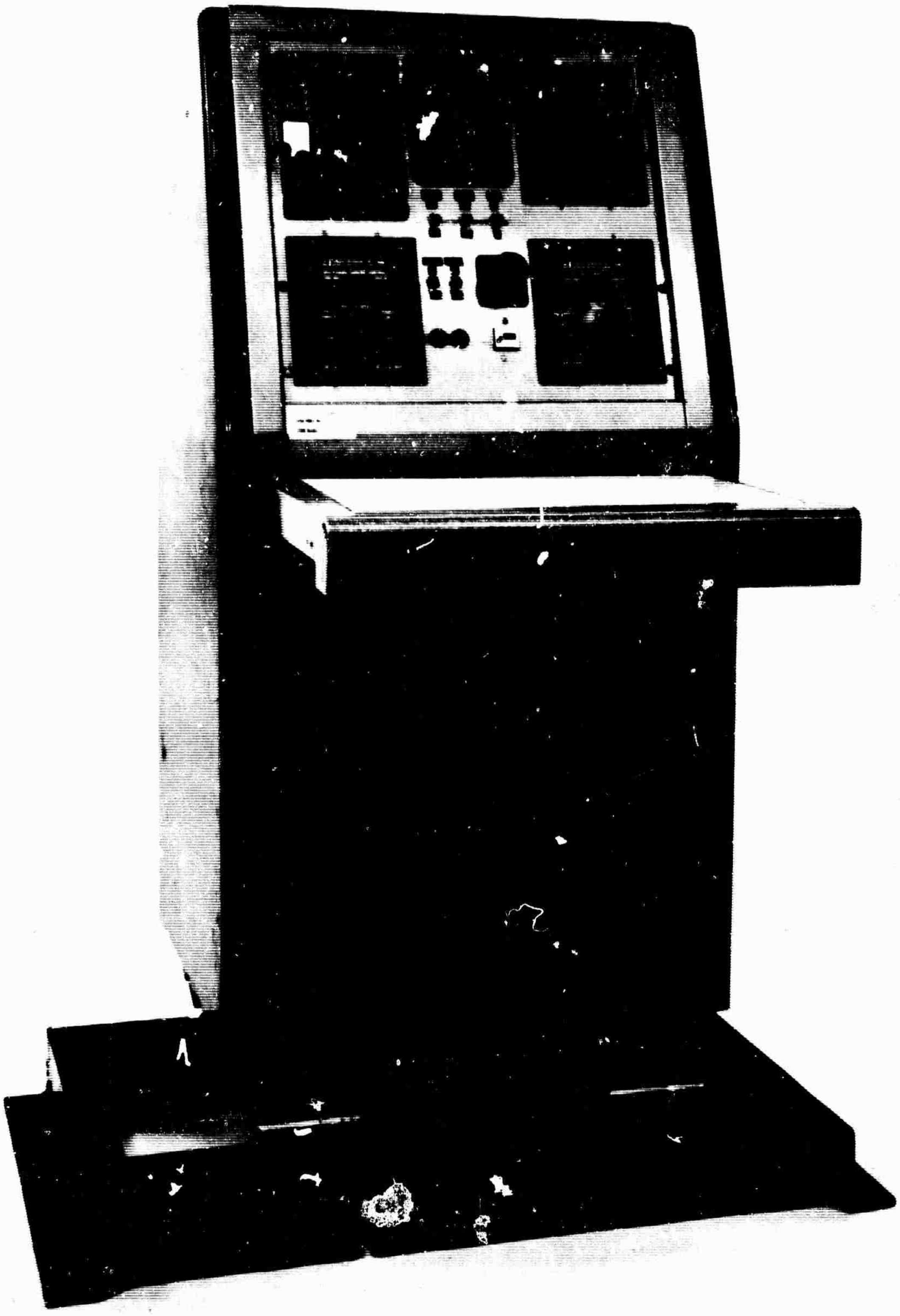

Figure 6.- Control console for modified multiband camera system.

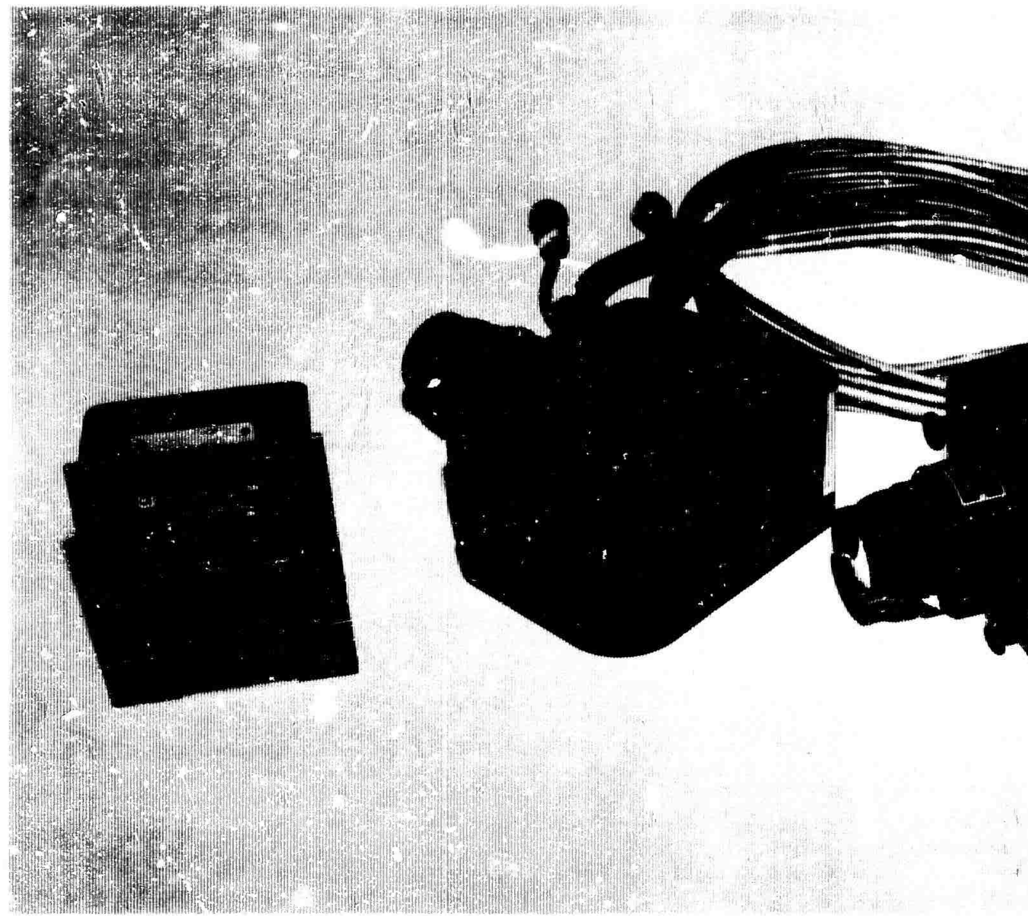

Figure 7.- Mitchell-Vinten F-95 70-mm cameras purchased to replace Maurer P-220's, with remote control boxes designed by Vidya.

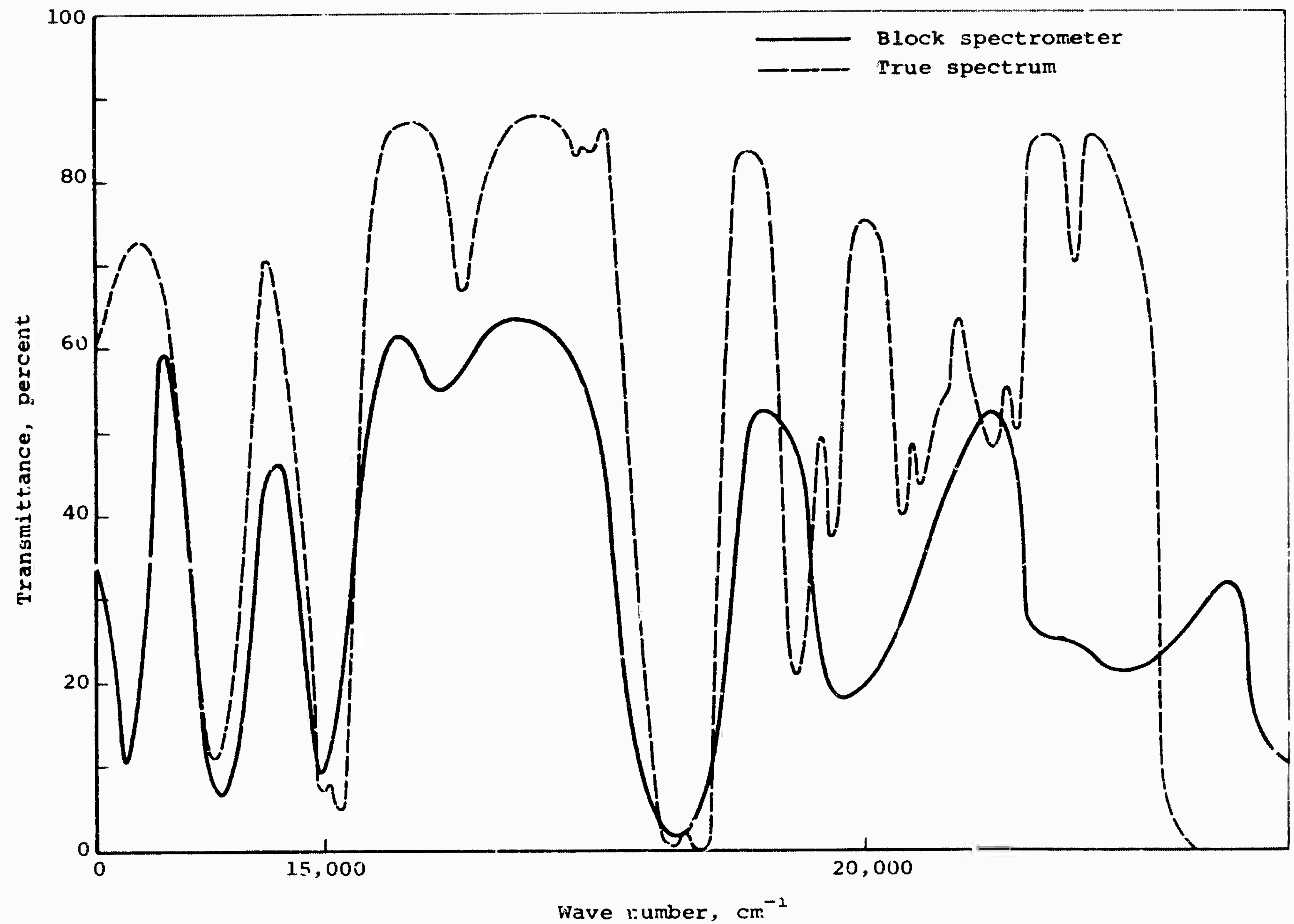

Figure 8.- Comparison of true spectral transmittance of dydimium glass with transmittance determined by Block spectrometer-I4L with light-biased cadmium selenide detector.

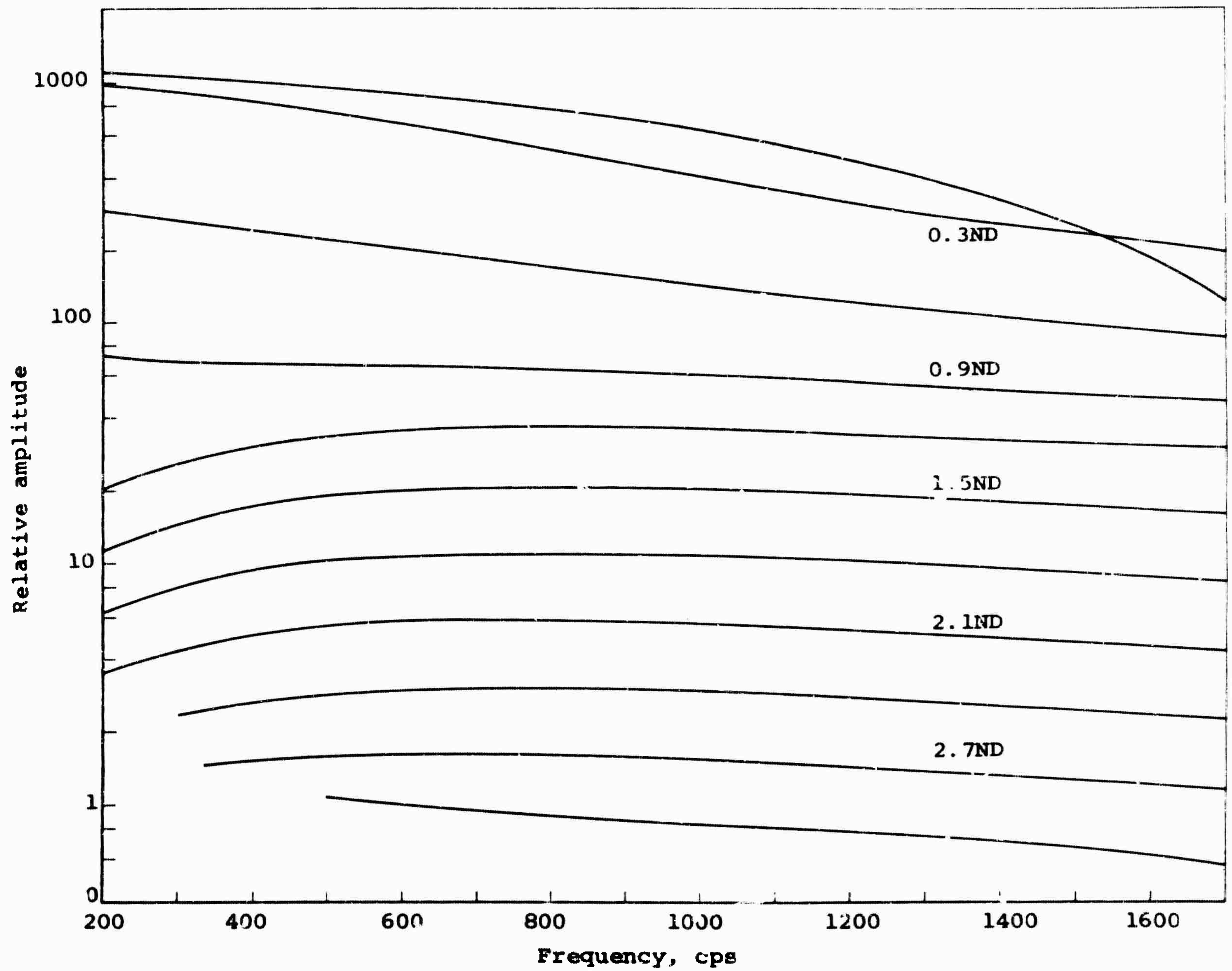

Figure 9.- Frequency response of Block spectrometer-I4L with light-biased cadmium selenide detector.

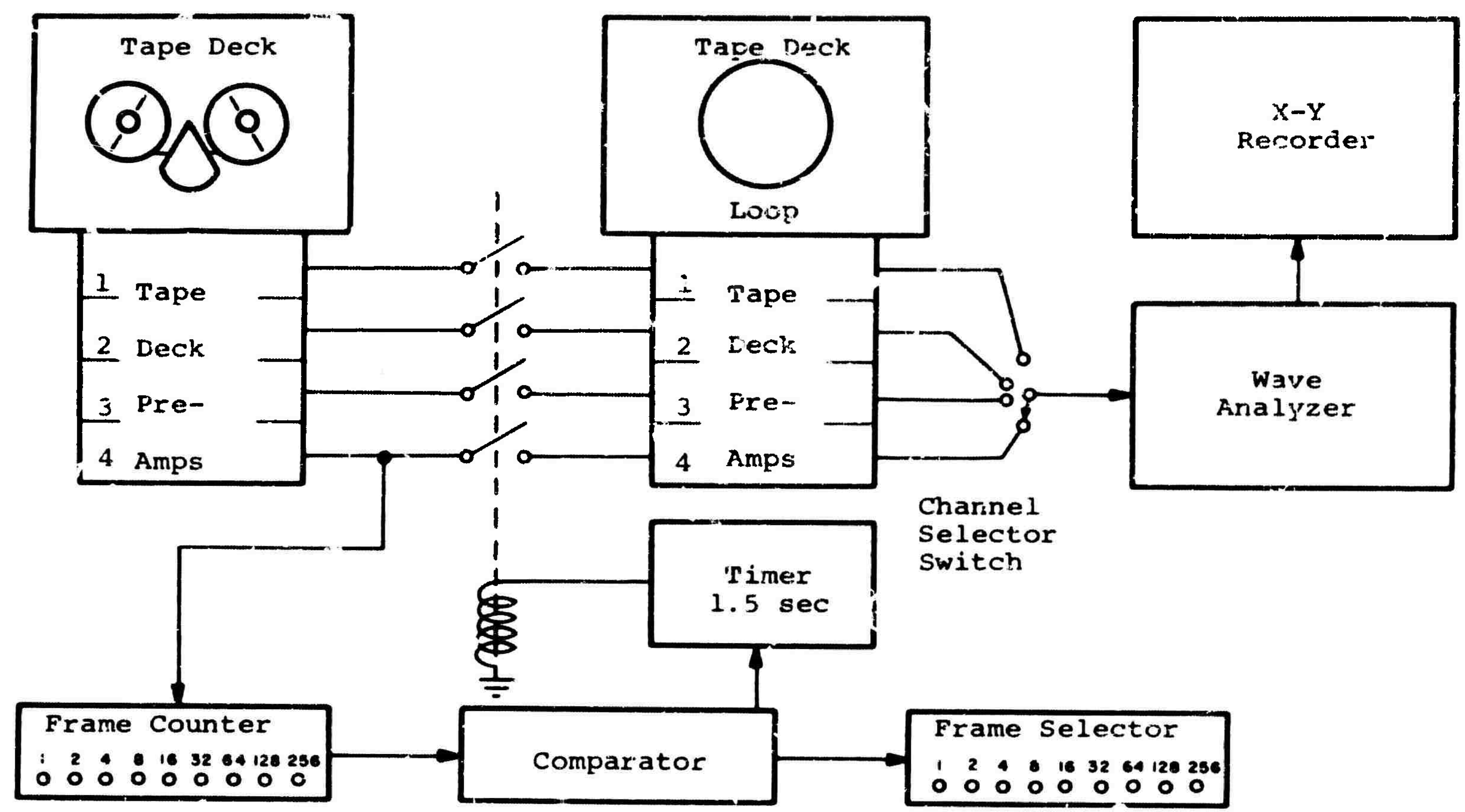

Figure 10.- Preliminary spectrometer data reduction.

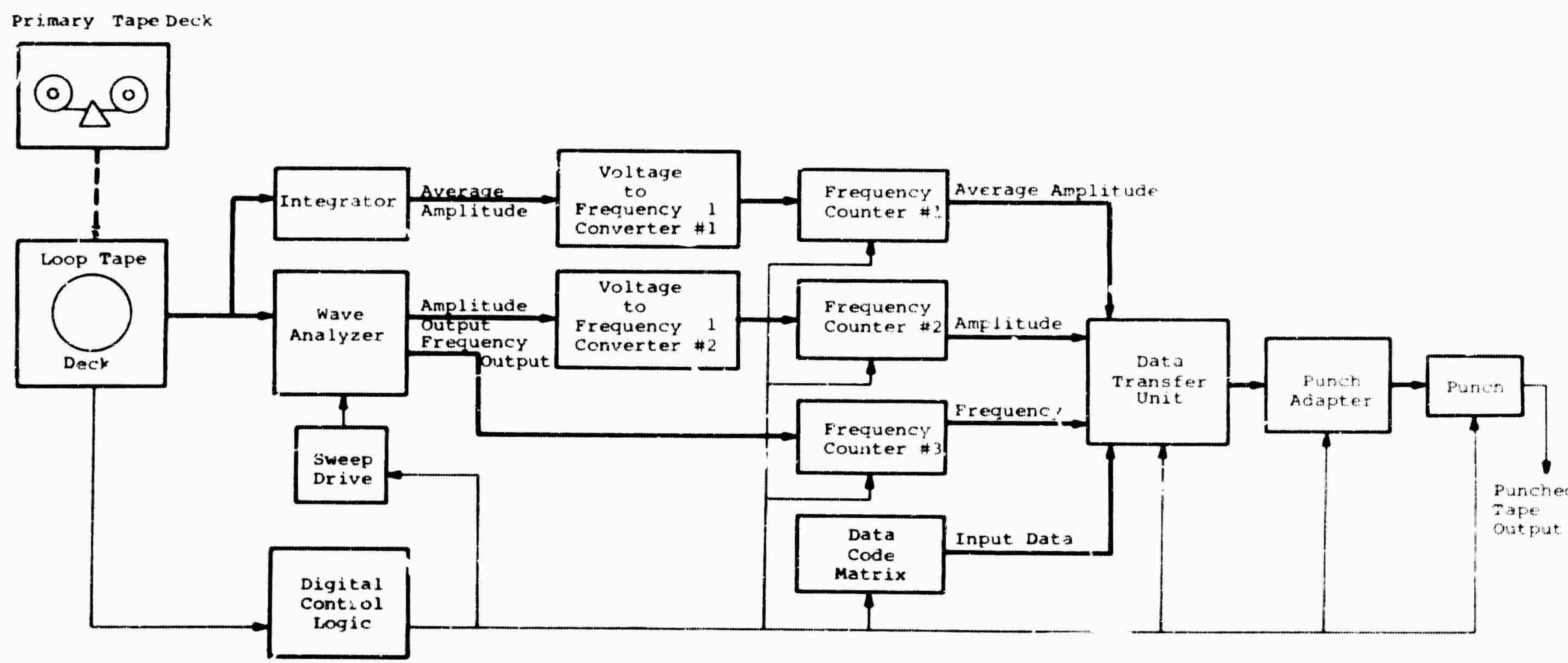

Figure 11.- Block diagram - data translation equipment.

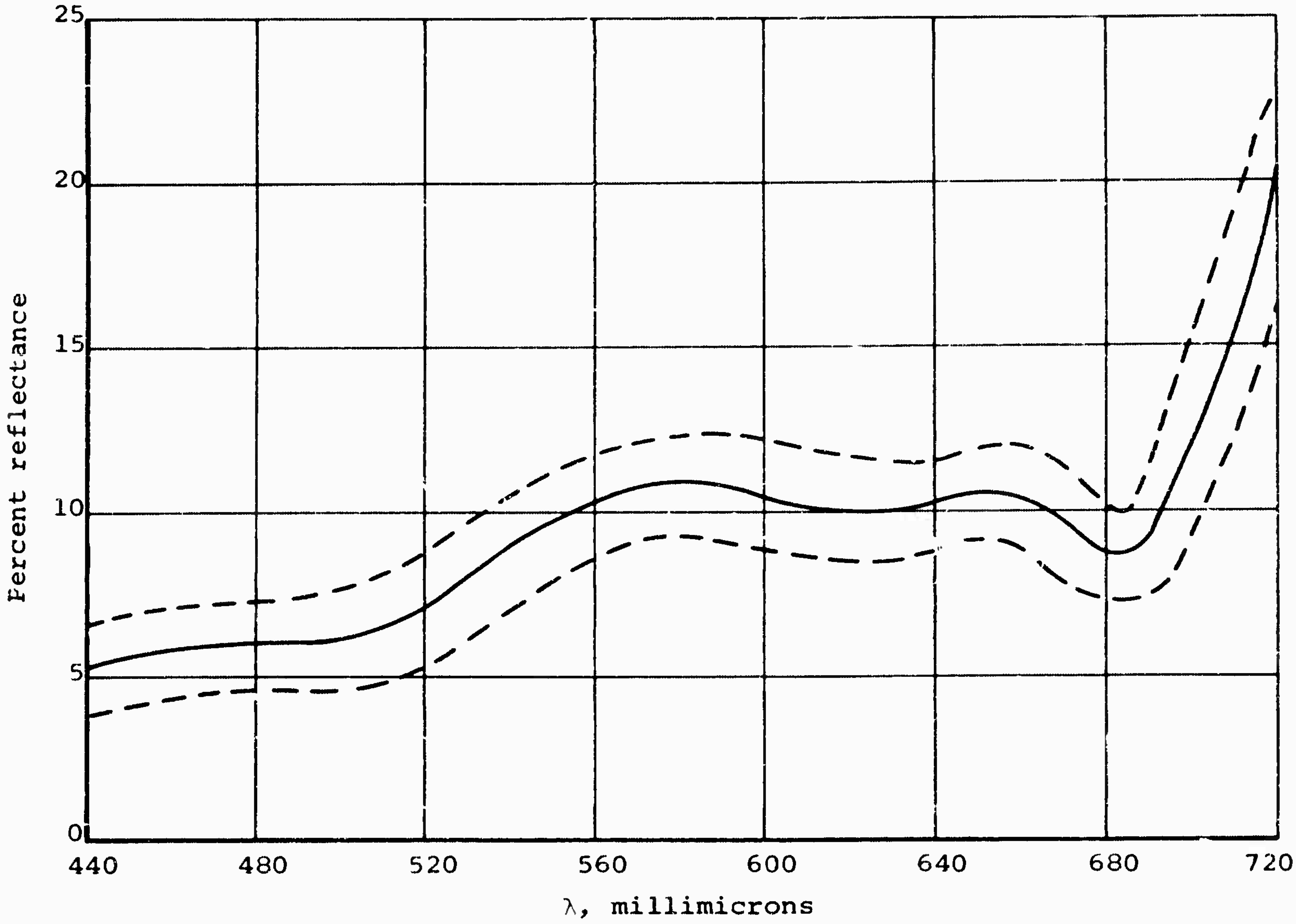

Figure 12.- Spectral reflectance of 1-day-old grapes with 1σ limits.

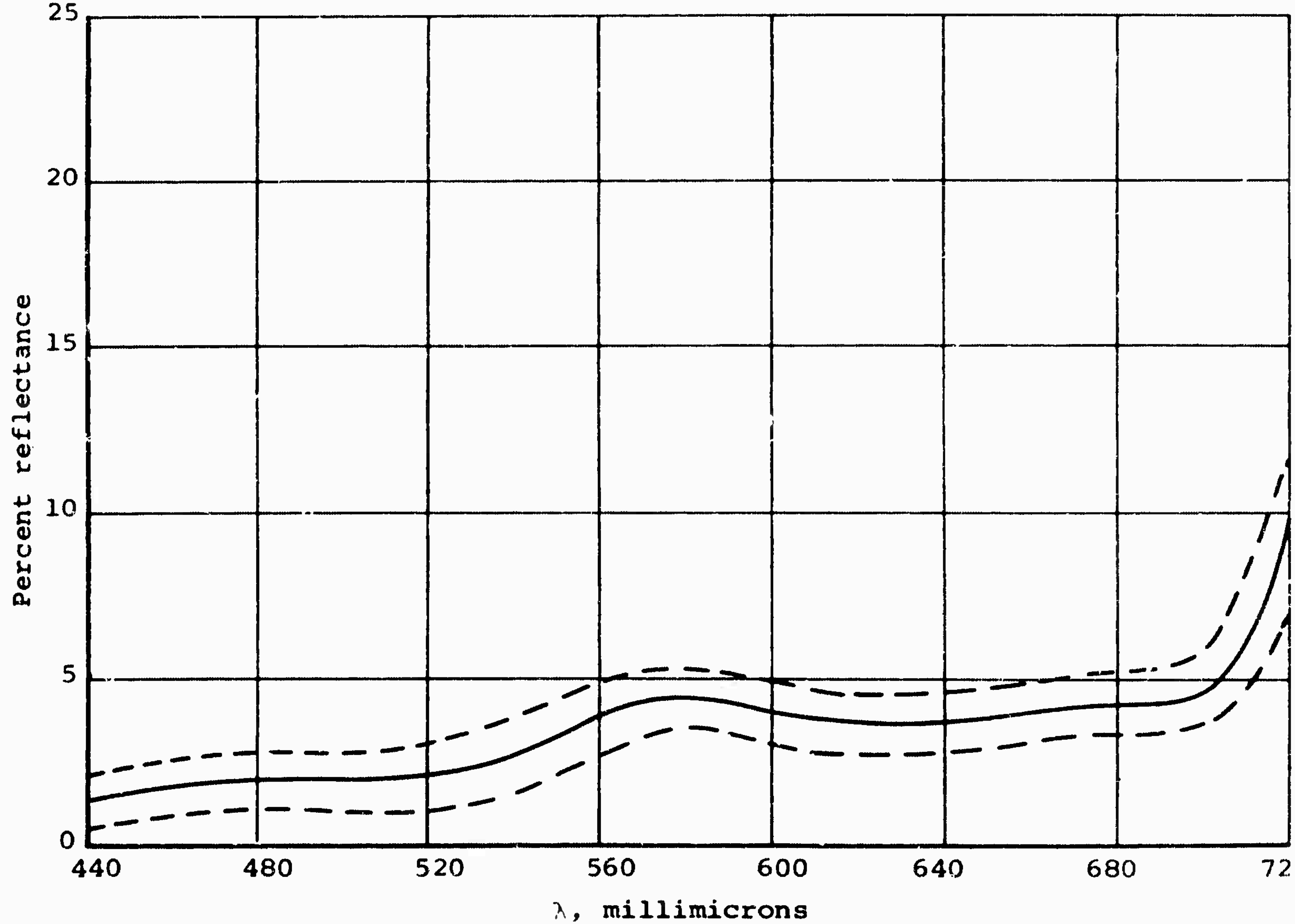

Figure 13.- Spectral reflectance of grape vines with 1σ limits.

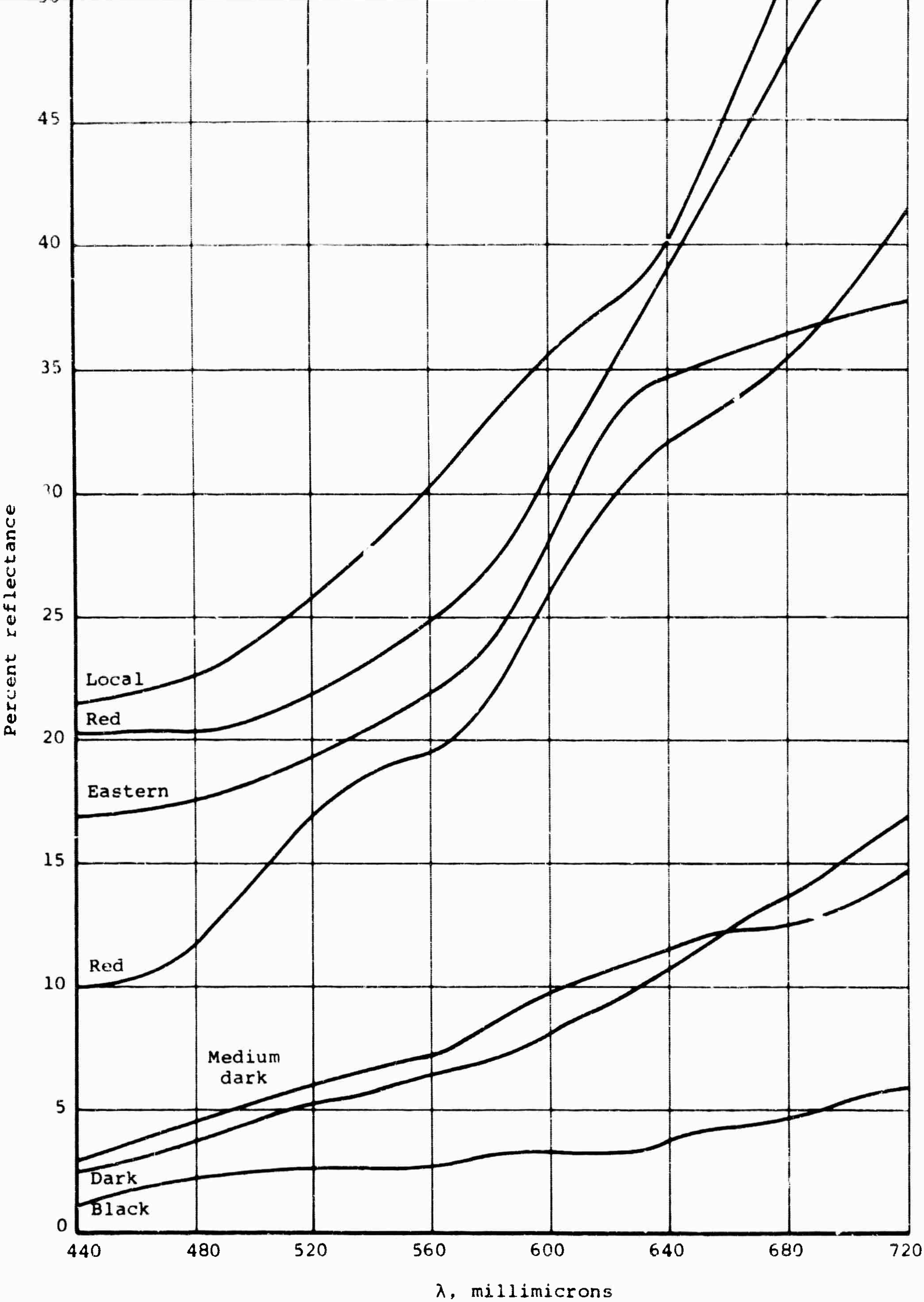

Figure 14.- Spectral reflectance of various soils.

APPENDIX A

LENS TESTS FOR VELA MULTIBAND CAMERA

(National Bureau of Standards[1])

Nine Schneider-Kreuznach Xenotar lenses, nominal focal length 150 mm, maximum aperture f/2.8, were tested at maximum aperture with the following filter and emulsion combinations. Development was in D-19 at 68° F for 3 minutes with continuous agitation.

Lens No.	Filter(s)	Emulsion
7352360	2B, 35, 38A	Plus X Aerographic
7352342	3, 47, 0.2ND	Plus X Aerographic
7352379	15, 65	Plus X Aerographic
7352370	57, 12, 155/166 Balzer, 0.4ND	Plus X Aerographic
7352369	90, 24	Plus X Aerographic
7352364	36, 15, 0.4ND	Plus X Aerographic
7352386	89B, 455/141 Balzer, 1.5ND	IV - R Infrared
7352346	87C, 0.4ND	IV - R Infrared
7352354	2.0ND	IV - R Infrared

Focal Length

Lens No.	Back Focal Distance (mm)	Equivalent Focal Length (mm)
7352360	108.60	150.39
7352342	108.50	150.16
7352379	107.77	149.89
7352370	108.16	150.10
7352369	108.42	150.07
7352364	108.72	150.19
7352386	110.06	150.56
7352346	108.86	150.71
7352354	108.45	150.38

The values of the focal lengths were selected to give best average definition across the entire negative and do not necessarily correspond to those values of focal length which give best definition on the axis. The probable errors of these determinations do not exceed ±0.10 mm.

---

[1] Extract from National Bureau of Standards Test Report No. 2.2/181053, June 17, 1964.

Distortion, mm

Lens No.	5°	10°	15°	20°	25°	30°
7352360	0.00	0.00	-0.02	-0.13	-0.47	-0.34
7352342	0.00	0.00	-0.01	-0.10	-0.40	-1.27
7352379	0.00	0.00	-0.01	-0.09	-0.38	-1.14
7352370	0.00	0.00	-0.02	-0.11	-0.39	-1.26
7352369	0.00	0.00	-0.01	-0.10	-0.38	-1.17
7352364	0.00	0.00	-0.01	-0.09	-0.35	-1.14
7352386	0.00	0.00	-0.01	-0.09	-0.35	-1.05
7352346	0.00	0.00	-0.02	-0.10	-0.37	-1.07
7352354	0.00	0.00	-0.02	-0.13	-0.48	-1.39

The values of distortion indicate the displacement of the image from its distortion-free position. A positive value indicates a displacement from the center of the plate. The probable error does not exceed ± 0.01 mm.

Resolving Power
Lines/Millimeter

Lens No.	0°	5°	10°	15°	20°	25°	30°
7352360 tan	27	27	23	16	16	11	14
7352360 rad	27	23	27	19	23	32	23
7352342 tan	19	19	16	14	16	14	10
7352342 rad	19	19	19	14	16	23	11
7352379 tan	32	32	27	23	23	16	19
7352379 rad	32	32	32	27	27	23	23
7352370 tan	27	27	27	27	23	23	16
7352370 rad	27	27	27	27	23	27	27
7352369 tan	32	32	27	23	23	16	16
7352369 rad	32	32	32	27	23	23	23
7352364 tan	27	27	27	23	16	16	16
7352364 rad	27	27	27	27	23	23	16
7352386 tan	27	27	27	23	23	11	19
7352386 rad	27	27	19	16	14	23	23
7352346 tan	19	16	16	16	16	16	14
7352346 rad	19	19	19	16	23	23	11
7352354 tan	19	19	16	16	16	16	8
7352354 rad	19	19	23	16	16	16	11

Values of resolving power are given at 5° intervals from the center of the field and are obtained by photographing test charts composed of patterns of parallel lines. The patterns of the test chart are imaged on the negative with the lines spaced in a geometric series of the fourth root of two lines to the millimeter. The row marked "tan" (tangential) gives the number of lines/mm in the image on the negative of the finest pattern of the test chart that is distinctly resolved into separate lines when the lines lie perpendicular to the radius drawn from the center of the field. The row marked "rad" (radial) gives similar values for the pattern of test lines lying parallel to the radius.

APPENDIX B

SPECTROMETER DATA-CORRECTION PROGRAM

```
      PUNCH 415
   96 CONTINUE
      CON(3)=1.
      CON(4)=1000.
      IF(CON(5)-FLAM(1))8,7,8
    7 ISPEC=1
      GO TO 10
    8 IF(CON(5)-FLAM(2))13,9,13
    9 ISPEC=2
   10 IF(CON(2))12,11,12
   11 ISTD=1
      GO TO 22
   12 ISTD=2
      GO TO 22
   13 IF(FLAM(1))14,21,14
   14 IF(FLAM(2))15,17,15
   15 PRINT 407,CON(5),FLAM(1),FLAM(2)
   16 PRINT 408
      PAUSE
      GO TO 4
   17 ISPEC=2
   18 IF(CON(2))19,20,19
   19 PRINT 409,ISPEC
      GO TO 16
   20 ISTD=1
      FLAM(ISPEC)=CON(5)
      GO TO 22
   21 ISPEC=1
      GO TO 18
   22 IF(CON(3)-1.)24,23,24
   23 IFREQ=1
      GO TO 27
   24 IF(CON(3)-2.)25,26,25
   25 PRINT 410,CON(3)
      GO TO 16
   26 IFREQ=2
   27 SUMY(ISTD)=0.
      SUMZ(ISTD)=0.
      DO 53 J=1,10
   51 READ 411, FX, FY, IDENT, NIP, FZ, PRT
      IF(PRT)51,52,51
   52 SUMY(ISTD)=SUMY(ISTD)+FY*.1*G(NIP)
   53 SUMZ(ISTD)=SUMZ(ISTD)+FZ*.1
      GO TO (55,54),ISTD
   54 PUNCH 405,SUMY(1),SUMZ(1)
      PUNCH 405, SUMY(2),SUMZ(2)
   55 CONTINUE
      NRET=1
      ZIP=10.
      IREAD=1
      GO TO 100
   28 FYM=FY
      FZM=FZ
      NRET=2
      GO TO 100
   29 FYO=FY
      FZO=FZ
      NRET=3
      GO TO 100
```

```
C         SPECTROMETER DATA CORRECTION PROGRAM.   8/10   CWH
C
  400 FORMAT(I5,15A4)
  401 FORMAT(1H1)
  402 FORMAT(29H SPECTROMETER DATA CORRECTION)
  403 FORMAT(2H   )
  404 FORMAT(2E15.7)
  405 FORMAT(2F5.0,I5,F5.0,5A1)
  406 FORMAT(30H PARITY ERROR IN PAPER TAPE = ,1A1,6H FREQ=,F6.0)
  407 FORMAT(22H ERROR. SPECTRO NUMBER,F6.0,7H MISSES,2F6.0)
  408 FORMAT(32H RESET PROGRAM WITH CORRECT DATA)
  409 FORMAT(28H ERROR. STANDARD FOR SPECTRO,I2,10H NOT GIVEN)
  410 FORMAT(26H ERROR. WRONG SPEED CODE =,F6.0)
  411 FORMAT(2F5.0,I4,I1,F5.0,5A1)
  412 FORMAT(40H EXTRAPOLATE IN FREQUENCY RESPONSE TABLE)
  413 FORMAT(I6,4X,F8.1,4X,F8.4)
  414 FORMAT(16H               WAVE)
  415 FORMAT(31H INDEX     LENGTH      RESPONSE)
      DIMENSION W(20),FN(2,100),RL(2,100),CON(6),G(10),RS(2,2,100),
     1FLAM(2),AF(2,100),RE(2,100),NCAL(2),NAF(2) ,SUMY(2),SUMZ(2)
      G(1)=1.0
      G(2)=3.
      G(3)=10.
      G(4)=30.
      G(5)=100.
      G(6)=300.
      G(7)=1.E+03
      G(8)=3.E+03
      G(9)=1.E+04
      G(10)=3.E+04
C
      PUNCH 401
      PUNCH 402
      PUNCH 403
    1 READ 400,NCAL(1),(W(J),J=1,15)
      PUNCH 400,NCAL(1),(W(J),J=1,15)
      NCAL1=NCAL(1)
      DO 2 J=1,NCAL1
      READ 404,FN(1,J),RL(1,J)
    2 PUNCH 404,FN(1,J),RL(1,J)
      READ 400,NCAL(2),(W(J),J=1,15)
      PUNCH 400,NCAL(2),(W(J),J=1,15)
      NCAL2=NCAL(2)
      DO 3 J=1,NCAL2
      READ 404,FN(2,J),RL(2,J)
    3 PUNCH 404,FN(2,J),RL(2,J)
      PUNCH 403
      FLAM(1)=0.
      FLAM(2)=0.
    4 READ 404,CON(5),SLOPE
      READ 405,FX,FY,IDENT,FZ
      CON(2)=IDENT
      IF(CON(2))97,96,97
   97 PUNCH 401
      PUNCH 402
      PUNCH 403
      PUNCH 400,IDENT
      PUNCH 404,CON(5),SLOPE
      PUNCH 414
```

```
   30 ICAL=NCAL(ISPEC)
      NRET=4
      FYP=FY
      FZP=FZ
      IREAD=1
      DO 35 I=1,ICAL
      Z=FN(ISPEC,I)
      IF(IREAD)31,33,31
   31 IF(Z-FZO)100,33,33
   32 FYM=FYO
      FYO=FYP
      FYP=FY
      FZM=FZO
      FZO=FZP
      FZP=FZ
      GO TO 31
C
C       INTERPOLATE QUADRATICALLY
   33 SUM=(Z-FZM)/(FZP-FZM)*(Z-FZO)/(FZP-FZO)*FYP
      SUM=(Z-FZM)/(FZO-FZM)*(Z-FZP)/(FZO-FZP)*FYO+SUM
      RS(ISPEC,ISTD,I)=SUM+(Z-FZO)/(FZM-FZO)*(Z-FZP)/(FZM-FZP)*FYM
      IF(ISTD-1)35,35,34
   34 RESP=RS(ISPEC,2,I)/RS(ISPEC,1,I)*RL(ISPEC,I)
      PUNCH 413,I,Z,RESP
   35 CONTINUE
      IF(IREAD)36,39,36
   36 READ 411, XI,YI,IDENT,NI,ZI,PRT
      IF(PRT)37,40,37
   37 CONTINUE
      GO TO 36
   38 ZIP=ZI
      IF(ABSF(IDENT)-900)36,36,39
   39 GO TO 4
   40 IF(ZI- ZIP)41,41,38
   41 IF(ABSF(IDENT)-900)37,37,39
C
C
C       SUBPROGRAM FOR INPUT AND CORRECTION OF ONE DATA POINT
  100 READ 411, XI,YI,IDENT,NI,ZI,PRT
      IF(PRT)101,107,101
  101 CONTINUE
      GO TO 100
  102 ZIP=ZI
      IF(ABSF(IDENT)-900)104,104,103
  103 IREAD=0
      GO TO (16,16,16,33),NRET
C
C       INTERPOLATE IN FREQUENCY RESPONSE TABLE
  104 FY=YI*G(NI)-SUMY(ISTD)-SLOPE*(ZI-SUMZ(ISTD))
      FZ=1.0E+03*CON(5)/ZI
      GO TO(28,29,30,32),NRET
  107 IF(ZI- ZIP)108,108,109
  108 IF(ABSF(IDENT)-900)101,101,103
  109 IF(NI-NIP)110,102,110
  110 NIP=NI
      GO TO 100
      END
```

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Lab. Office of Aerospace Research United States Air Force Bedford, Massachusetts

13. ABSTRACT

The nine-lens camera built as a prototype instrument for Project VELA has been redesigned and rebuilt, and is operating well. Redesigned or replaced parts in the new camera include: a stainless-steel shutter curtain; lenses individually focused for best resolution in each band: adjustable fiducial markers which allow optical registration in composite printing; new optical projection frame counters; a new electrical remote-control box and system console. The Maurer P-220 cameras of the prototype multiband system have been replaced with Mitchell-Vinten F-95 70-mm reconnaissance cameras.

The 14L Block spectrometer has been intensively tested, and previous difficulties with this instrument have been isolated. Its unsuitability appears to be due to the nonlinear response of the light-biased cadmium selenide detector. The silicon solar detector proved satisfactory.

The preliminary system of analyzing spectrograms by visual inspection was replaced with two computer programs: one to convert spectral data from paper tape to IBM cards, and a second to calibrate and correct the data at selected points over the spectrum.

At the request of the project monitor, a review and appraisal of multiband spectral analysis of the SHOAL event was submitted under Vidya Report No. 164.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Multiband camera Multiband spectral reconnaissance Airborne spectrometry Spectral data analysis Project VELA - airborne reconnaissance						

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